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DESIGN AND EXPERIMENTAL CONSTRUCTION OF A SIX-STROKE ENGINE WITH WATER INJECTION

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ABSTRACT

Internal Combustion Engines can be found under the hoods of 98% of the estimated 1.2 billion cars in the world. The quest for engines with better power and greater fuel efficiency has been persistent for a great number of years. New ideas and technologies have been incorporated into the current system in order to reduce the consumption of fuel. A six-stroke I. C. engine will radically improve on the concept of a four-stroke I. C. Engine. It will increase the fuel efficiency and improve the heat dissipation of the engine, thereby eliminating the need for a radiator. The six-stroke engine concept will add two strokes of water to the original four-stroke cycle. The fifth stroke in the cycle will act as an auxiliary power stroke. This type of engine will have positive implications on the environment as it will reduce emissions. The paper gives a detailed description of the design changes that need to be incorporated for the engine to run on a six-stroke cycle. It also gives an insight into the various thermodynamic process changes that occur on converting a four-stroke engine into a six-stroke engine along with the various parameters that have to be taken into consideration. The Crower Six Stroke engine is the basis for this design idea.

KEYWORDS: Efficiency, Engine-Head, Injection, Six-Stroke, Water

INTRODUCTION

Decline in Fossil Fuels

Combustion of fuel is the fundamental driving force of an Internal Combustion Engine. Oil being a non-renewable source of energy is bound to get exhausted over time. The Oil & Gas Journal, in 2010 estimated that around 1,354 billion barrels of oil reserves were left on the planet. We use approximately 90 billion barrels of oil every year. There are extremely infinitesimal chances of discovering any new oil reserves. We are left with around 15 years' worth of oil for our consumption.

Switch to Electric Vehicles

Electric Vehicles first came into existence in the mid-19th century, when electricity was among the preferred methods for motor vehicle propulsion, but were soon taken over by the Internal Combustion Engine. During the last few decades, environmental impact of the petroleum-based transportation infrastructure, along with the declining oil levels, has led to renewed interest in an electric transportation infrastructure.The acceptance of electric cars in the automotive market has led to a tremendous increase in the sale of electric cars. As of September 2014, more than 600,000 highway-capable plug-in electric passenger cars and light utility vehicles have been sold worldwide, consisting of more than 356,000 all-electric cars and utility vans, and about 248,000 plug-in hybrids.

Electric cars aren't selling nearly as well as many predicted, research suggests a host of reasons including a basic

lack of familiarity, a high price tag, misconceptions about the cars and ineffective government incentives are responsible for the apathetic response.

Need for a Six Stroke Engine

It is estimated that it will take at least 25 more years for a majority of the I. C. Engine vehicles to be replaced by Electric Vehicles. According to the current rate of oil consumption, the oil reserves are estimated to last for only up to 15 years. It is exceedingly necessary for us reduce the gasoline consumption in order to fill the energy gap left by oil, only then will those reserves give us an estimated additional 7 years' worth of oil, prolonging the duration of utility of the resource. The oil prices in the global markets are also rising; this has prompted vehicle owners to look out for vehicles with better fuel economy. A six stroke engine concept will enable us to achieve this without having to bring about an enormous change in the overall design of the engine and can be also incorporated in the current running vehicles by means of well-designed modification kits.

The estimated reduction in fuel consumption is around 40% due to the addition of two extra strokes as the fuel injection will take place every sixth stroke as compared to every fourth stroke in the original four-stroke I. C. Engine cycle. The engine under study is a derivation of the Crower six-stroke engine concept.

METHOD

Six-Stroke Engine Design

The six-stroke engine is a modification of the conventional four-stroke engine in order to add two additional strokes of water. In the case of a two valve per cylinder engine this is achieved by incorporating an electronic water injector and an extra valve, on the head of the engine, for the injection and exhaustion of water. In the case of a four valve per cylinder engine, the final two strokes are obtained by dedicating two existing valves, replacing one with an injector and using the other for the exhaustion of water. Increasing the diameter of the air intake and exhaust valves may also be necessary.

The six strokes in the engine cycle are:

- Intake
- Combustion
- Compression
- Exhaust
- Water Injection (Auxiliary Stroke)
- Exhaustion of Water

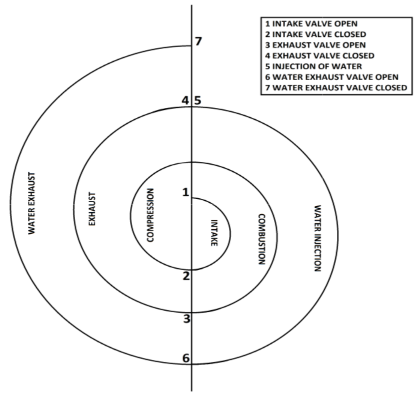

Figure 1: Ideal Valve Timing Diagram for a Six-Stroke Engine

In a six-stroke engine, the fifth stroke starts at the end of the air exhaust stroke, when the piston is at TDC; the electronic injector will spray water in the cylinder. A manual water spray may also be used and operated by means of a camshaft, albeit with lower mechanical efficiency. The water that enters the combustion chamber uses the heat of combustion and gets converted into steam. The post exhaust temperatures ranging between 150^{O}C and 300^{O}C, on account of the elimination of the radiator system, along with the spraying of water, facilitate the conversion of water into steam. This steam expands and exerts pressure on the piston combined with the rotational inertia of the engine, causing the auxiliary power stroke. When the piston reaches BDC, the water exhaustion valve opens and the steam is pushed out of the combustion chamber by the upward motion of the piston. Heat that is generally dissipated through the radiator is utilized to increase the total work of the engine. The amount of work obtained from the same quantity of fuel increases, thus improving thermal efficiency.

In a six-stroke engine, the first four strokes are that of the conventional engine. This part of the engine cycle is based on the Otto Cycle. The fifth and sixth strokes are the injection and exhaustion of water respectively and will be governed by the Water Cycle.

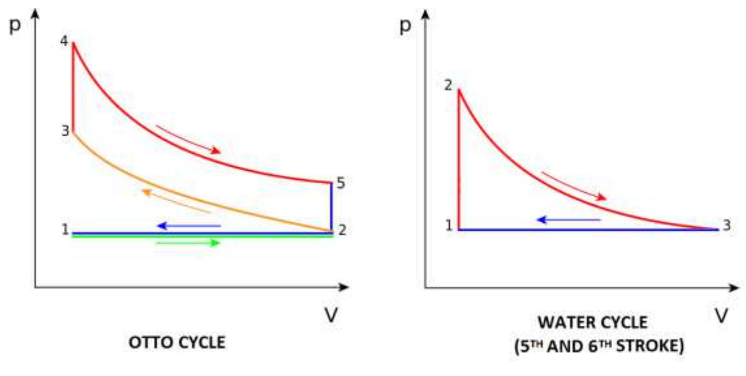

Figure 2: P-V Diagrams of the Otto Cycle and the Subsequent Water Cycle (6)

The P-V diagram of the Water Cycle concludes that during the injection of water, when the piston is at TDC, there is a constant-volume heat transfer, as indicated by the Process 1-2. This is the instantaneous conversion of water into steam, which increases the pressure on the piston without any change in volume. The Process 2-3 is an adiabatic (isentropic) expansion, which is the auxiliary power stroke. The Process 3-1 is the exhaust of steam into the atmosphere at constant pressure. This process does not take into account the heat rejected by the steam when the piston is at BDC as the amount of heat left would be negligible.

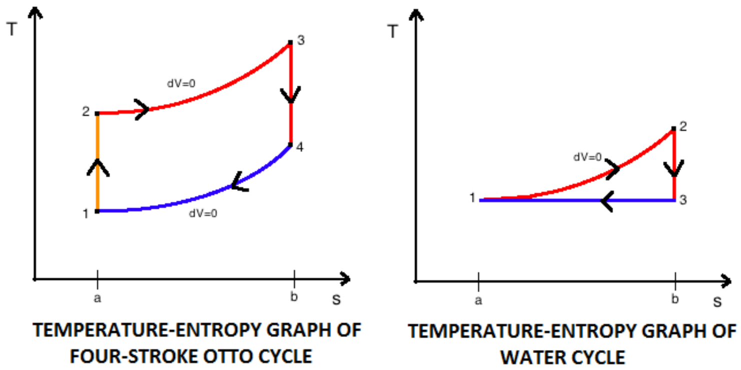

Figure 3: T-S Diagrams of the Otto and Subsequent Water Cycle (6)

In the T-S diagram of the water cycle, the Process 1-2 indicates that there is a rise in the temperature of the water that is injected, and the injection of water also increases the entropy of the system. In Process 2-3, temperature falls due to adiabatic expansion at constant entropy. The exhaustion of steam brings down the entropy to its original position, as observed in Process 3-1.

A three cylinder as well as a four cylinder engine can be converted into a six-stroke engine. Balancing of a three cylinder six-stroke engine is relatively easier. The six-stroke cycle in three and four cylinder engines generally have a power stroke alongside an auxiliary power stroke, depending on the firing order and crank pin angle. This arrangement assists the auxiliary power stroke in the event of excessive engine loads. The same concept can be extended to engines with the number of cylinders in multiples of three and four respectively. It is not advisable to incorporate a six stroke cycle on single cylinder engines as the auxiliary power stroke alone may not be able to sustain the engine loads, thus heavily relying on the rotational inertia of the engine to push the piston down. It may eventually cause the engine to stall. If a six-stroke cycle is implemented on a two cylinder engine, then there would be a 360^{O} crank angle rotation between any power and auxiliary power strokes, thus giving similar outputs as that of a six-stroke single cylinder engine on a load. Nonetheless, it may be difficult to install a water tank on two wheelers, the major beneficiaries of the single and double cylinder engines.

Cylinder	1	2	3	
Crank Pin Angle	0	120	240	
Stroke Advance Angle	0	60	120	Crank Rotation Angle
1st Stroke	combustion	water exhaust	intake	0
2nd Stroke	exhaust	intake	compression	180
3rd Stroke	water injection	compression	combustion	360
4th Stroke	water exhaust	combustion	exhaust	540
5th Stroke	intake	exhaust	water injection	720
6th Stroke	compression	water injection	water exhaust	900

Figure 4: Stroke Cycle of a 3-Cylinder Six-Stroke Engine

In a three-cylinder engine, the crank pin angles are 120^{O} apart. This arrangement enables us to have a 60^{O} overlap of a combustion stroke and an auxiliary power stroke. The firing order of the engine is 1-3-2. The figure shows the firing order of the six-stroke engine over one cycle. Any stroke in the first cylinder indicates the start of that particular stroke. The stroke advance angle is the angle through which the crankshaft has rotated in the particular stroke. The crankshaft angles of all the strokes in the second and third cylinders are given with respect to the first cylinder, which will either be at TDC or BDC depending on the stroke.

The combustion and auxiliary combustion strokes that overlap each other are indicated through identical coloring.

The water injection stroke, indicated in grey, in the second cylinder is not overlapped by a combustion stroke; it is rather overlapped by a compression and a water exhaust stroke from first and third cylinders respectively. This particular stroke will be in the best position to take advantage of the rotational inertia of the engine as it will only occur in the middle cylinder of a 3-cylinder engine with a 1-3-2 firing order.

Cylinder	1	2	3	4	
Crank Pin Angle	0	180	180	0	Crank Rotation Angle
1st Stroke	combustion	water exhaust	compression	intake	0
2nd Stroke	exhaust	intake	combustion	compression	180
3rd Stroke	water injection	compression	exhaust	combustion	360
4th Stroke	water exhaust	combustion	water injection	exhaust	540
5th Stroke	intake	exhaust	water exhaust	water injection	720
6th Stroke	compression	water injection	intake	water exhaust	900

Figure 5: Stroke Cycle of a 4-Cylinder Six-Stroke Engine

In a four-cylinder engine, the crank pin angles are generally 180^{O} apart in pairs. This arrangement enables us to have a complete overlap of the auxiliary power stroke with a combustion stroke for at least two cylinders. Generally the firing order of the engine is 1-3-4-2 and varies depending on the manufacturer. The figure shows the firing order of the six-stroke engine over a complete cycle. A similar identical coloring method is used as in the stroke cycle of a three-cylinder engine, to indicate an overlap of an auxiliary power stroke with a combustion stroke. In this case there is complete overlap of the water injection stroke. The water injection strokes highlighted in grey are not overlapped by combustion strokes, thus having to rely on the rotational inertia of the engine.

Crucial modifications have to be made to the head of the engine in order to achieve six strokes. It requires modification of the intake and the exhaust manifolds in order to add an injector and outlet for water. The head, in case of a two valve per cylinder engine, may be machined and an injector seat and an extra exhaust valve may be added.

It is advisable to have the inlet for air and injector for water on the same side of the camshaft. If they are on the opposite sides of the camshaft, then, on running of the engine, the intake of air (first stroke), which takes place immediately after the exhaust of steam (sixth stroke) might lead to some amount of steam being trapped inside the combustion chamber, as the air intake will be in a direction opposite to the exhaust of steam. This will lead to the poor scavenging of the steam. It will also degrade the overall performance of the engine. Keeping the inlets on the same side gives better scavenging during the exhaust of air as well as steam.

In a six-stroke engine, three valves and an injector have to be operated with a different number of strokes between the actuation of the corresponding valves of air and water respectively. On starting the engine, the intake valve for air would actuate and after two strokes of compression and combustion respectively, the exhaust valve for air would actuate. In a conventional engine, the intake valve for air would open immediately after the closing of the exhaust valve; but in the case of a six stroke engine, following the closing of the exhaust valve, the two strokes for water injection and exhaustion take place. Hence, the intake and the exhaust valves for air, alternatively actuate after every two strokes. The mechanism that controls the flow of water, on the other hand, actuates the injector and exhaust valves on consecutive strokes; the injector would again spray water after the four strokes of a conventional I. C. Engine cycle. In order to facilitate this sequence of the actuation of valves, a secondary camshaft placed vertically above the primary camshaft is incorporated. This secondary camshaft controls the injector and the exhaust valve for water. The primary camshaft will only be limited to controlling the air intake and exhaust valves.

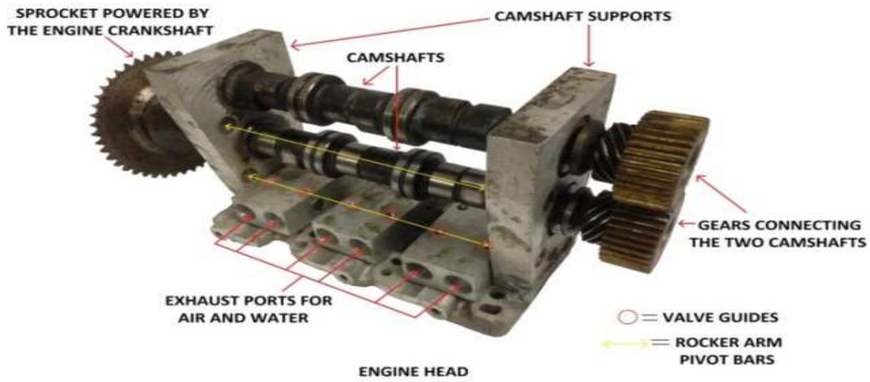

Figure 6: Image of the Reconstructed Engine Head without Some Essential Components for Better Observation

The cam profiles of the two camshafts have to be same. The original camshafts of the engine may be used, but the rotation speed of the camshaft, relative to the crankshaft has to be changed. In a conventional engine a camshaft rotates 90^{O} for every 180^{O} rotation of the crankshaft. But in the case of a six-stroke engine, the camshaft has to rotate only 60^{O} for every 180^{O} rotation of the crankshaft. This will enable us to incorporate six cam positions at the six strokes. A chain or a belt drive may be used to accomplish this arrangement.

The placements of the rocker arms (followers) are also different from conventional positions. The point of contact of the four rocker arms would each lie at the vertices of a horizontal (flat side up) hexagon inscribed in the base circle of the cam. The contact points of rocker arms actuating the valves for the intake and exhaust of air would be positioned at the two opposite vertices that lie on the base circle diameter parallel to the piston head. The contact points of the rocker arms controlling the injector and the exhaustion valve of water would lie on the two higher vertices if the crankshaft rotates clockwise when viewed from the flywheel, and on the lower vertices if the crankshaft rotates anticlockwise when viewed from the flywheel; assuming that the intake ports lie on the right of the camshaft when viewed from the flywheel. Albeit, the rocker arms actuating the air valves and water controllers would lie on the primary and secondary camshafts respectively.

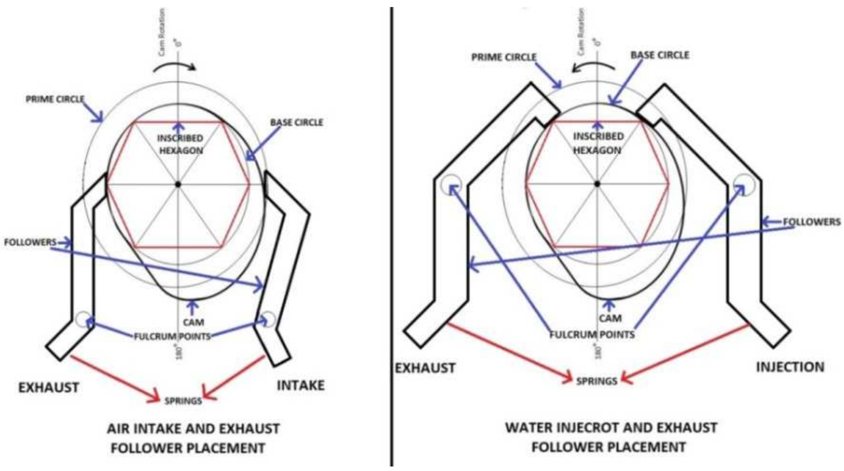

Figure 7: Rocker Arm Placement When Viewed from the Flywheel End

The primary camshaft always rotates in the same direction as that of the crankshaft. The secondary camshaft must rotate in a direction opposite to that of the primary camshaft. If the primary camshaft is rotating in a clockwise direction when viewed from the flywheel, then in order to actuate the water injector immediately after the air exhaust closes, the

secondary shaft has to rotate in an anticlockwise direction, since the intake ports for air and water lie on the same side of the camshafts. The arrangement of two camshafts rotating in opposite directions is easy to achieve with a pair of gears with a unit gear ratio.

A standard electric fuel pump may be used to achieve the function of water injection. The volume flow rate of 4.25 liters/minute at 40 psi pressure for the water pump should suffice. This function may also be achieved by utilizing the mechanical water pump used in the radiator system, as the radiator system will be redundant; on condition that it gives the desired amount of volume flow rate for water. Plastic or rubber pipes, that can sustain the rated pressure, may be used to redirect the water from the pump to the intake ports. The connector at the water injector may utilize the provision provided for the attachment of the original air intake manifold, and will have to be modeled accordingly. In a two valve per cylinder engine, provisions will have to be made for this arrangement during the machining of the extra valve. The steam exhaust may be allowed to escape into the atmosphere, or may be utilized for any other purpose and will have to be channeled accordingly. In the case of an electric water injector, the ECU controlling the injector must be programmed to spray water on every sixth stroke in accordance with the firing order. In the case of a mechanically operated water injector, a mechanism must be incorporated to connect the lever actuating the injector to the secondary camshaft; addition of return springs may be necessary if the provision is not available with the injector.

The gear that drives the spark plug distributor need not be changed as it will operate on a six stroke cycle due to its unit ratio with the camshaft. The adjustment in the spark timing will be incorporated through the changed rotation speed of the camshaft. In the case of a distributor-less ignition system or any other electronically controlled ignition system, the necessary changes have to be made to the spark timing in order to incorporate a six stroke cycle. In the case of a fuel injected engine, the ECU has to be programmed in order to spray the fuel on every sixth stroke in accordance with the firing order. Fuel delivery modifications are not necessary on a carbureted engine. The stoichiometric air-fuel ratio or the original ratio set by the engine manufacturer may be used.

The same principles may be applied to diesel engines, in order to convert a four-stroke diesel engine into a six-stroke engine. The temperature in the cylinder of a diesel engine after exhaust is lower than that of a gasoline engine. This is because of the auto-ignition temperature of diesel being lower than that of gasoline. Care must be taken to ensure that there is enough temperature for the conversion of water into steam during the water injection stroke. The absence of spark plugs would eliminate any ignition related modifications. On the other hand, fuel injection timing will have to be modified in the case of every diesel engine.

Experimental Engine Specifications

Engine

Maruti Suzuki F8B Engine

Engine Specifications (Original)

Displacement: 796 cc (49 cu in)

Bore x Stroke: 68.5 x 72.0mm

Valves per cylinder: 2

Number of cylinders: 3 inline

Fuel type: Gasoline

Power: 40 HP at 5000 rpm

Torque: 57 Nm at 2500 Rpm

Rpm limiter: 7000 rpm

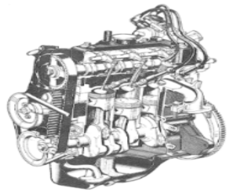

Figure 8: Maruti 800 Engine (F8B)

Engine Performance (Original)

Maximum speed: 130 km/h (81 mph)

0–100 km/h (0–62 mph): 18.8 seconds

1/4-mile: 28.5 seconds

Fuel Economy (Original)

Mileage highway: 19 km/l (5.3 l/100 km; 45 mpg)

Mileage city: 16 km/l (6.3 l/100 km; 38 mpg)

Mileage overall: 17 km/l (5.9 l/100 km; 40 mpg)

Engine Modifications

The F8B is a 3-cylinder carbureted engine. The crank pins are at 120^{O} with respect to each other. The firing order of the engine is 1-3-2. It fulfills all the criteria to be converted into a six-stroke cycle. Hence, engine has been selected.

Engine Head

Figure 9: Original Engine Head Machined Engine Head (before Drilling for Spark Plugs)

This engine has two valves per cylinder. It has to be converted into three valves and an injector port, in order to function on a six-stroke cycle. The original valves were filled using TIG welding process. The position and inclination angles of the extra valves were designed in accordance with the original head design. The valves were later machined through a CNC machining process. Grooves were incorporated for the valve seats. The spark plugs were also repositioned according to convenience. The water injector seat was later fabricated by further machining of the water intake port.

Sufficient clearance for the water injector was maintained.

Air Intake Port Diameter: 18.5mm Air Exhaust Port Diameter: 16mm

Water Injector Diameter: 16mm Water Exhaust Port Diameter: 16mm

Angle of inclination (with respect to vertical): 18^{O}

Camshafts

Two camshafts have to be incorporated on the engine head. To facilitate this arrangement, the original camshaft supports were machined and redesigned aluminum supports, which can accommodate the dual camshaft design, were welded onto the engine head. The original belt drive, used for rotating the camshaft was replaced by a chain drive. The two camshafts were connected to each other by gears.

Crankshaft Sprocket: 15 Camshaft Sprockets: 45

Sprocket Ratio: 1: 3 (crankshaft: camshaft) Camshaft gear teeth: 36 (1: 1 ratio)

Distance between two Camshafts: 56.8mm

Valves

The number of valves has to be increased from 6 to 9. Extra valves of the same engine, along with the valve seats, were procured. The valve seats were press-fitted into the grooves.

Intake Valve seat I.D.: 18.5mm Intake Valve seat O.D.: 26.5mm

Exhaust Valve seat I.D.: 16mm Exhaust Valve seat O.D.: 24.5mm

Water Injector Seat I.D.: 16mm Water Injector Seat O.D.: 26.5mm

Rocker Arms

Aluminum rocker arms were designed for the intake and exhaust ports. The position of the pivot bars was also changed and incorporated in the camshaft supports. The four pivot bars were placed in pairs, vertically one below the other, on either side of the camshaft.

Water Injector

Denso fuel injectors along with a fuel pump module were used for water injection. The ECU was tuned to spray water on every sixth stroke. The stock fuel rail and injection from a Maruti Suzuki F8D engine was used. The F8D engine is a 12 valve MPFI upgrade of the engine under study.

CONCLUSIONS

A six-stroke engine has been envisioned and fabricated with various approaches. The experimental design proposal enables us to convert currently functioning Internal Combustion engines into a six-stroke cycle along with the fabrication of upcoming six-stroke engines. The experimentally fabricated engine could not be tested on loads due to structural deficiencies and modest build quality, as well as the unavailability of resources.

The paper deals with the various components of the engine that have to be modified or replaced in order to

model the engine on a six-stroke cycle. The six-stroke engine modification promises dramatic reduction in the fuel consumption and pollution caused by an internal combustion engine. It enables lower engine running temperature therefore eliminating the need for a radiator. The amount of work achieved from the quantity of heat induced also increases, thus increasing thermal efficiency. The use of such a technology shall have many positive ramifications on the environment.

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